# Light new physics with underground accelerators

**Maxim Pospelov**

University of Victoria/Perimeter Institute, Waterloo

E. Izaguirre, G. Krnjaic, MP, work in progress

S. Karshenboim, D. McKeen, MP, 2014

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

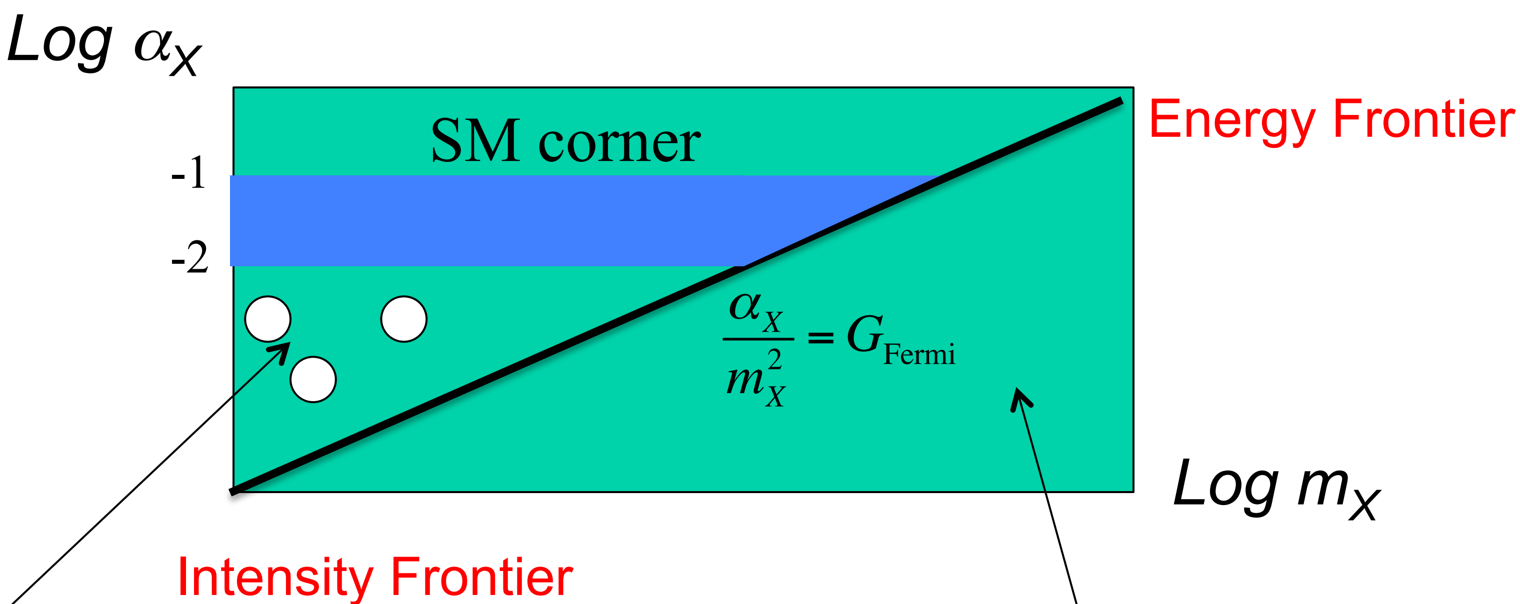
# Outline of the talk

1. Introduction.
2. Results of the $\mu$H PSI experiment and why they are puzzling when compared to *e-p* data.
4. Current constraints on "dark forces for $\mu$H". Problems with every proposal.
5. Constraints on scalar *e-p* scattering force, and a possible search at underground accelerators
5. Conclusions

# Main idea

- New physics with mass scale of several 100 keV and very weak couplings to electrons & nucleons can be a “blind spot” for various astro + cosmo constraints. Can be motivated by recent discrepancies e.g. “proton charge radius”
- When mass < few MeV (up to 20 MeV), the new states can be accessed via *nuclear reactions*.
- Underground facilities have unique possibilities for producing new states using low-energy proton accelerators, and detecting their decay/scattering with large & clean neutrino detectors (such as Borexino, SuperK, etc.)
- A large progress in covering the parameter space is possible with relatively modest investment.

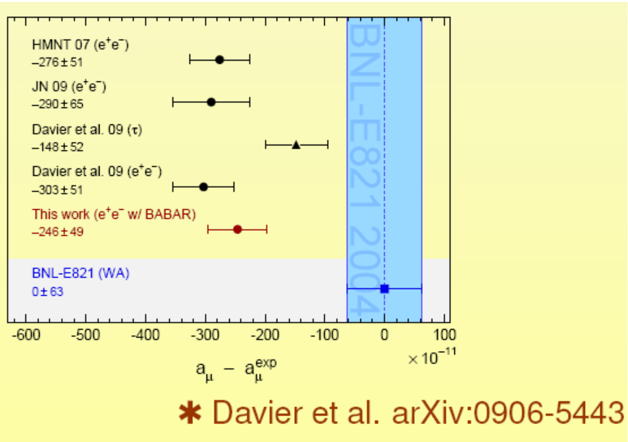
# "Stronger than weak" New Physics

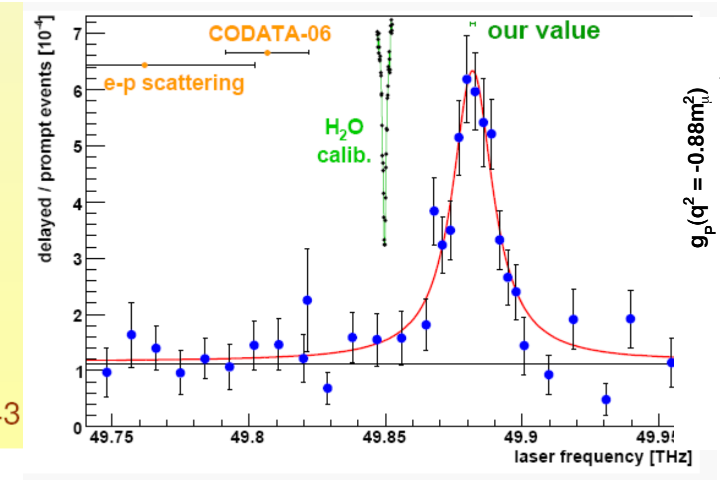


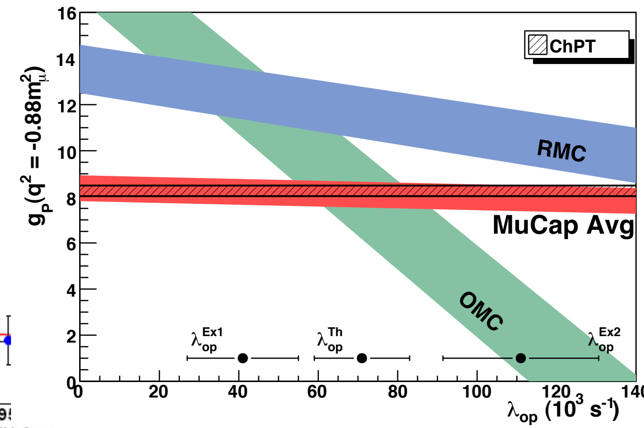

If you see new effects like e.g. $\mu \rightarrow eee$, EDM etc it'll be here (can be 1000 TeV, difficult to access, and no pressing need for UV completion)

If you see NP effects in muon-H LS, it has to exist at $O(10^4\, G_F)$ level, deep inside the SM corner (e.g. Swiss cheese picture) *You have to specify how this NP fits into SM. Real chance to check in other exp*

# Muons are misbehaving; have we tested them enough?



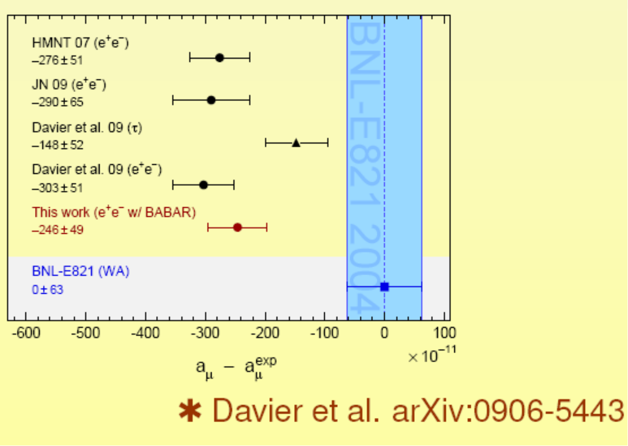



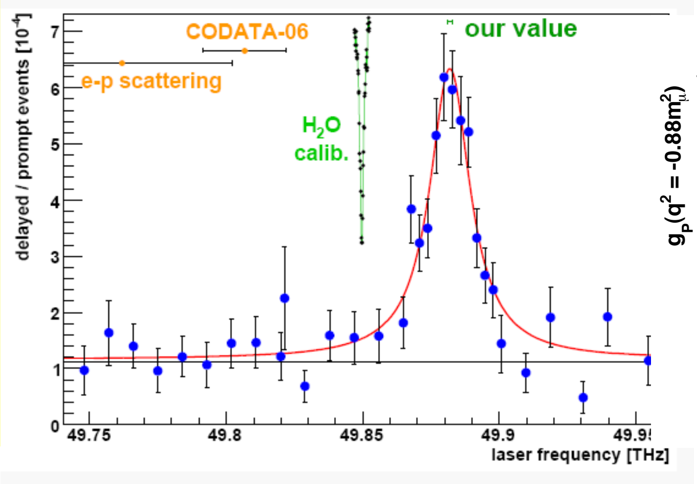



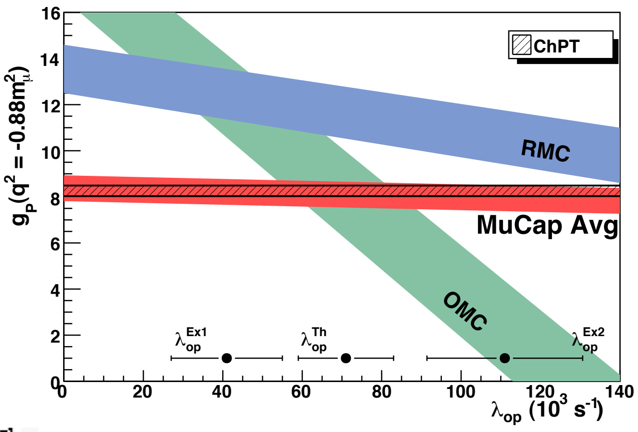

*May be something happens with muonic "neutral" channels at low energy.* We do not know – therefore it would be quite foolish not to explore additional possibilities of testing "NC-like" signatures in muons at low energy.

Resolution of current puzzles ($r_p$, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches *of new phenomena* associated with muons.

# Muons are misbehaving; have we tested them enough?




**Can result from**

**New Physics at**

**100 GeV scale or MeV**

**scale**

**IF it is NP, it can only be light**

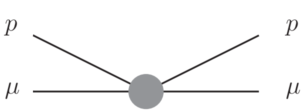
# Why should we care about $r_p$ problem?

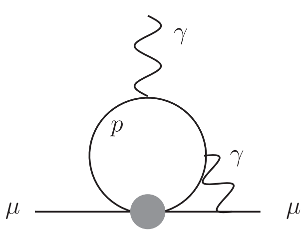
G-2 experiment "migrated" from BNL to Fermilab. Its cost can approach hundred M$

$r_p$ problem is a huge challenge: if by any chance the muon-proton interaction is "large": either the two-photon strong interaction diagram or "light new physics", then g-2 is not really calculable with required precision!

$$\Delta\mathcal{L} \simeq C(\bar{\psi}_\mu \psi_\mu)(\bar{\psi}_p \psi_p),$$

$$C \text{ needs to be } \sim (4\pi\alpha) \times 0.01 \text{ fm}^2$$



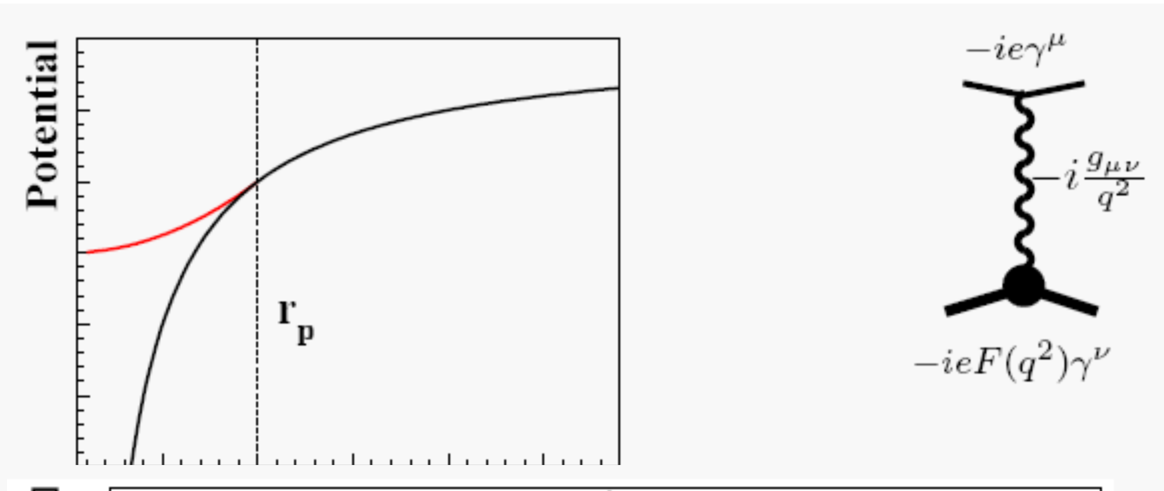




$$\Delta(a_\mu) \sim -C \times \frac{\alpha m_\mu m_p}{8\pi^3} \times \begin{cases} 1.7; & \Lambda_{\text{had}} \sim m_p \\ 0.08; & \Lambda_{\text{had}} \sim m_\pi \end{cases}$$

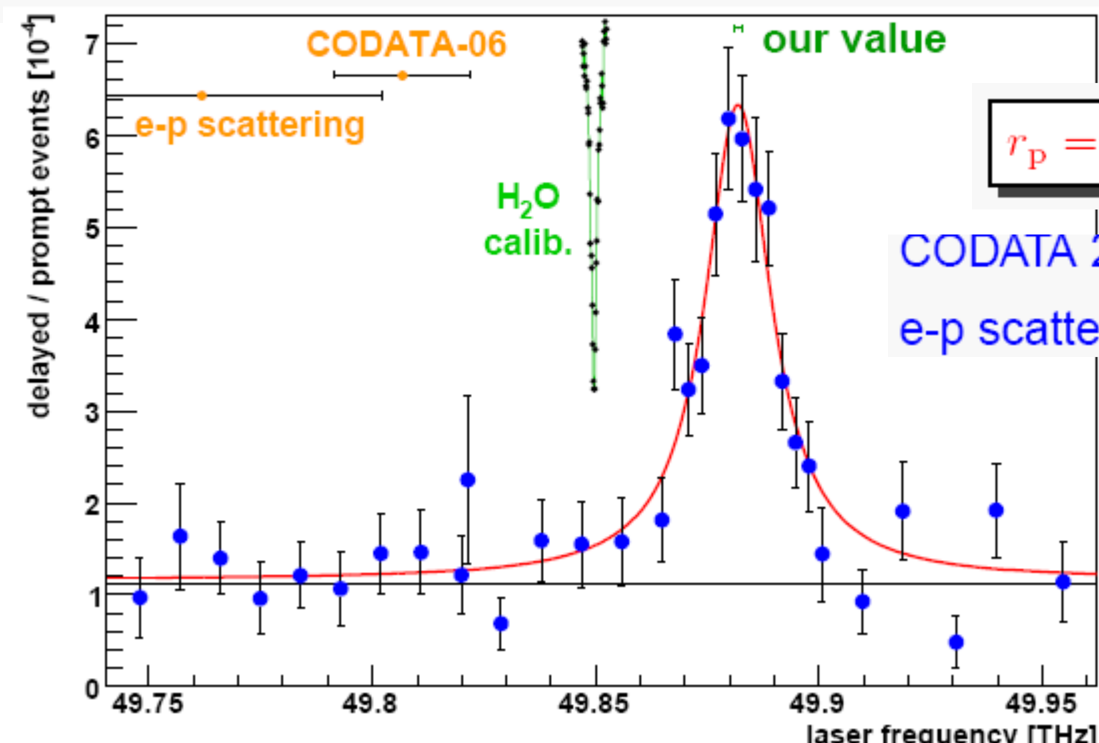
$$5 \times 10^{-9} \lesssim |\Delta(a_\mu)| \lesssim 10^{-7}.$$

Shift is much larger than hadronic LBL error! Larger than discrepancy…

# Muonic hydrogen and $r_p$




The experiment is very hard to make work [low counting rates, hard to find resonance]. But once resonance is found, even O(100) events will lead to robust $r_p$ measur.




$$r_{\mathrm{p}} = 0.84184(67)\ \mathrm{fm} \qquad u_r^{\mathrm{th}} = 8 \times 10^{-4}$$

CODATA 2006: $r_{\mathrm{p}} = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_{\mathrm{p}} = (0.895 \pm 0.018)$ fm (2%)

# Current status

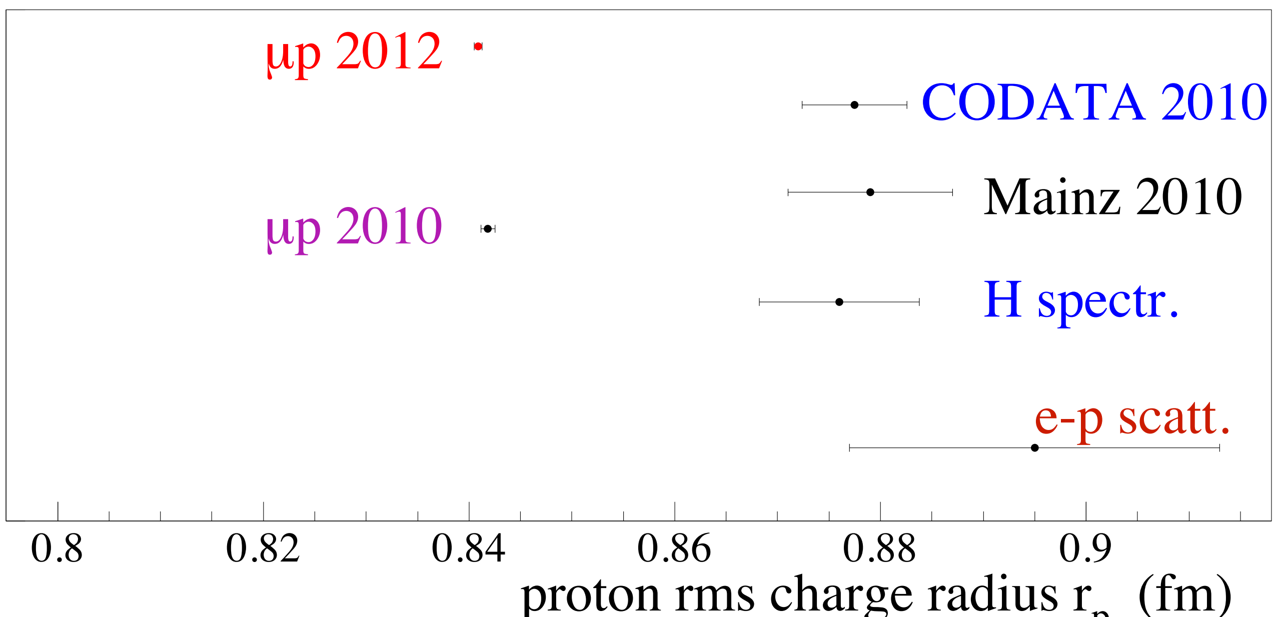
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz — R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz — preliminary

$\nu(2S_{1/2}^{F=0} \to 2P_{3/2}^{F=1})$ = 54611.16(1.04) GHz — preliminary

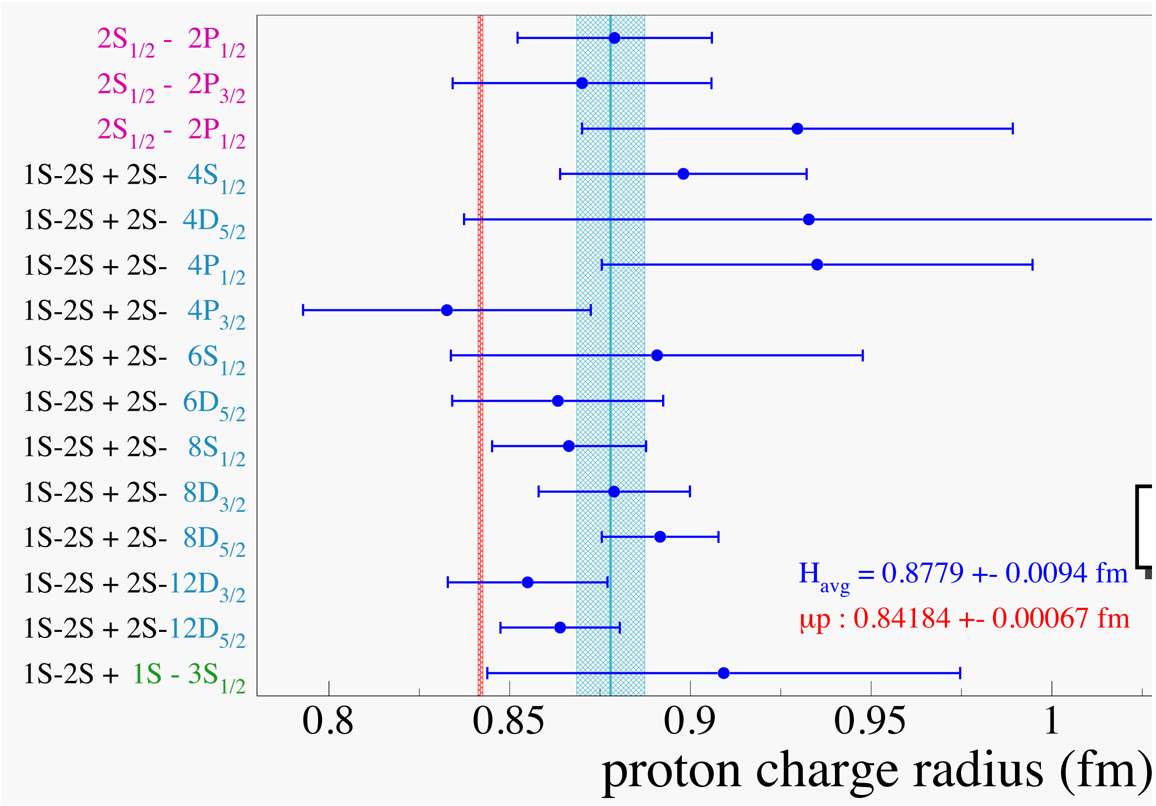
Proton charge radius: $r_{\mathrm{p}}$ = 0.84089 (26)$_{\mathrm{exp}}$ (29)$_{\mathrm{th}}$ = 0.84089 (39) fm (prel.)

$\mu\mathrm{p}$ theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)




Importantly, *Zeemach radius* extracted from 2 lines is perfectly consistent with previous (normal hydrogen) determinations

# $r_p$ from Normal Hydrogen




Red line – muonic hydrogen result

Blue band – fitted value of $r_p$ from precision spectroscopy of normal hydrogen.

It is a serious 5σ discrepancy (but only when one takes into account many transitions!)

# What are the possible origins of discrepancy?

1. Problems with experiments: either with μH, or with scattering and normal H. ??
2. Problems with QED calculations, either in μH or eH ??
3. A completely miscalculated "hadronic effect" in the two-photon proton polarization diagram ??

…

4. May be some very new forces (= new physics) are at play that would have to be much weaker than EM and much stronger than EW. ??

More info on the whole issue can be found in the slides from a recent workshop:
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Workshop/Talks

# New physics ~~explanations~~ attempts

Barger, Marfatia, Chiang, Keung; Tucker-Smith, Yavin; Batell, McKeen, MP; Brax, Burrage; Carlson, Winslow.

*Common features of these attempts*:

1. If *all* experiments and SM calculations are to be believed, it got to be a new force, that differentiates between e-p and $\mu$-p.
1. Light, e.g. ~10 MeV in mass, particles are involved as careers.
2. Typically one or more of other constraints require additional tuning (g-2 of the muon, neutron scattering) – and one has to "model-build" yourself out of trouble.
3. Except our paper nobody tried to actually see how such a new force would fit

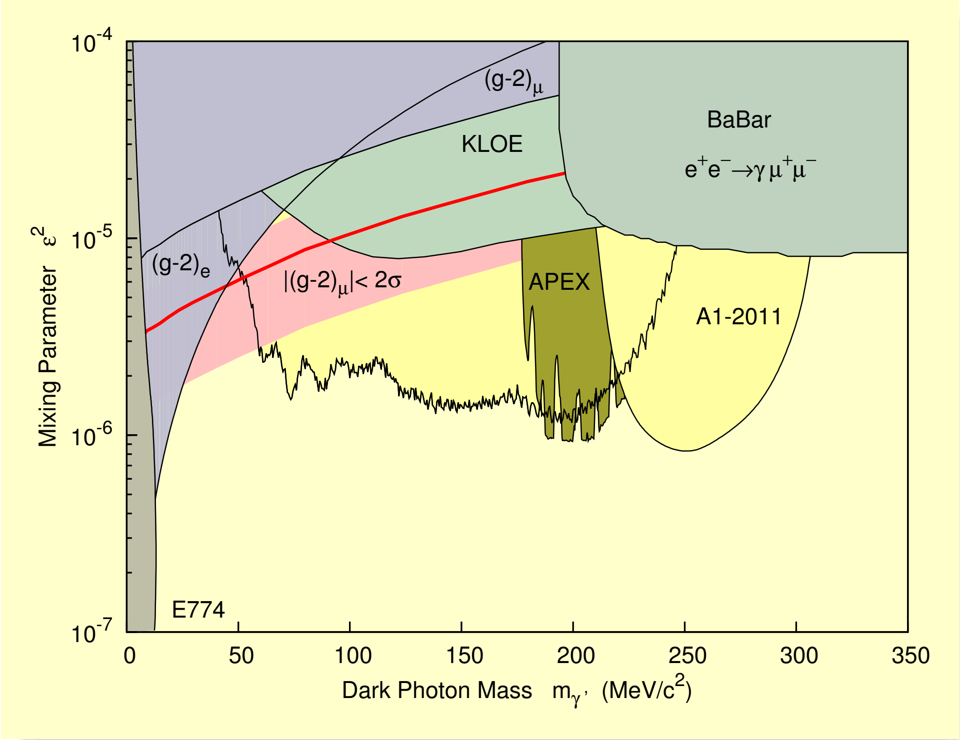
*Nobody on this list would ever claim that these are very natural or believable models. At this point it is more of an intellectual exercise.*

# *Huge progress in constraining "dark photon"(Jlab, Mainz, BaBar, KLOE… )*

Extended mass range (data taking 2012, preliminary)

- Extension to lower mass region
- Several beam energy settings
- Lower mass limit: minimum angle between spectrometer

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$




Recent summary of constraints: H. Merkel et al (Mainz)

Almost all g-2 band is covered now – but there is an island left at ~30 MeV

# "Dark photon" model cannot explain all discrepancies

Dark photon model (Okun, Holdom) can explain larger $r_p$ measured in scattering compared to atoms. It cannot explain difference between $r_p$ extracted from normal and muonic H Lamb shift.

So, the expected pattern for a dark photon model aligns *apparent* charge radii according to $q^2$:

$$r_p(\text{normal H}) < r_p(\text{muonic H}) < r_p(\text{e-p or } \mu\text{-p scattering})$$

However, what is observed is this pattern:

$$r_p(\text{muonic H}) < r_p(\text{normal H}) \sim r_p(\text{e-p scattering})$$

One needs a new interaction, that distinguishes muons and electrons, for example, $(\mu\gamma_\nu\mu)(p\gamma_\nu p)$ or $(\mu\mu)(pp)$ with coefficient $\sim 10^4 G_F$

# New U(1) forces for right-handed muons

Batell, McKeen, MP, PRL 2011 – Imbeds a new force into SM

Despite considerable theoretical difficulties to build a consistent model of "muonic forces" relevant for $r_p$ discrepancy, gauged RH muon number could be still alive:

$$\mathcal{L} = -\frac{1}{4}V_{\alpha\beta}^2 + |D_\alpha\phi|^2 + \bar{\mu}_R i \not{D} \mu_R - \frac{\kappa}{2}V_{\alpha\beta}F^{\alpha\beta} - \mathcal{L}_m$$

Main logical chain leading to this:

1. Scalar exchange is disfavored because of the neutron scattering constraints, and meson decay constraints. (We need to *revisit* this in light of possible mu-D discrepancy)
2. Vector force has to NOT couple to left-handed leptons – otherwise huge new effects for neutrinos. Then has to couple to RH muons, $V_\alpha \bar{l}\gamma_\alpha l \subset V_\alpha(c_1\bar{L}\gamma_\alpha L + c_2\bar{R}\gamma_\alpha R),\ c_1 \neq -c_2.$

# Even more "ad hoc" model for muonic force

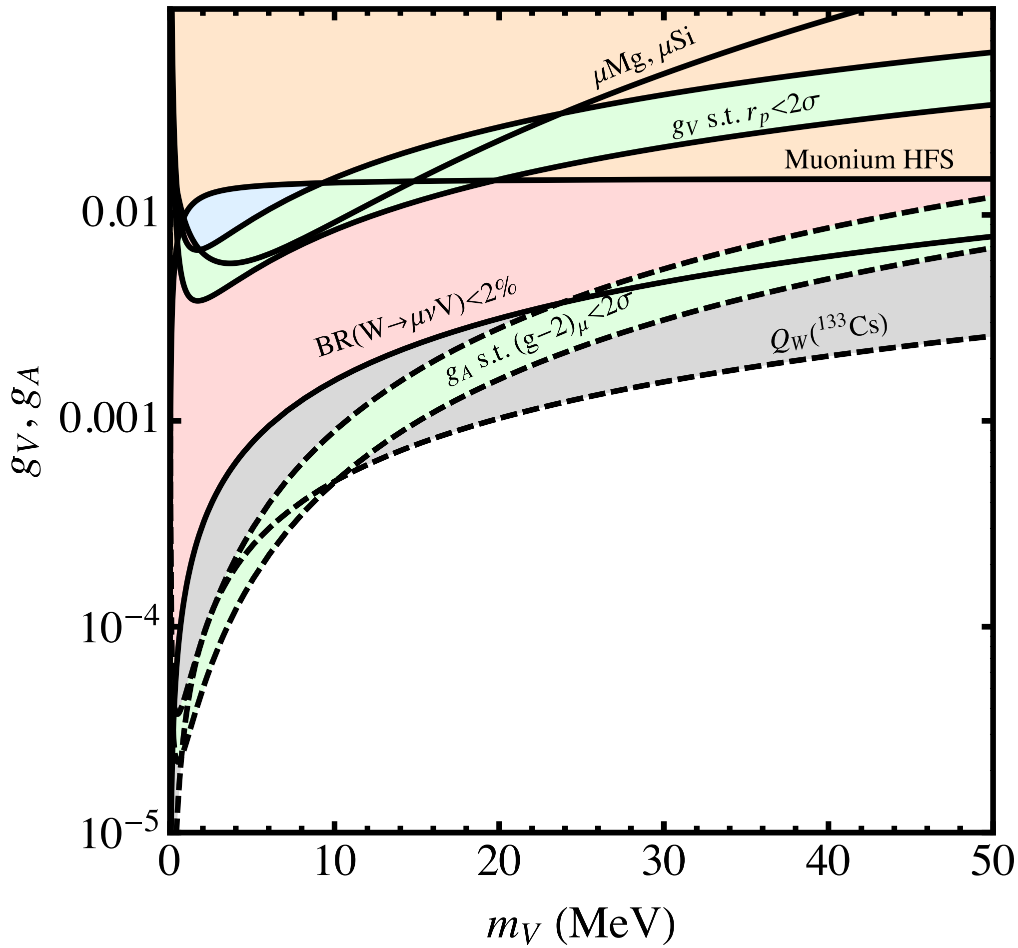
For the sake of discussion, one can introduce a model with additional couplings for muons without caring too much of embedding it into the SM.

$$\begin{aligned}\mathcal{L}_{\rm int} = -V_\nu \left[\kappa J^{\rm em}_\nu - \bar{\psi}_\mu (g_V \gamma_\nu + g_A \gamma_\nu \gamma_5)\psi_\mu\right] \\ = -V_\nu \left[e\kappa \bar{\psi}_p \gamma_\nu \psi_p - e\kappa \bar{\psi}_e \gamma_\nu \psi_e \right. \\ \left. -\bar{\psi}_\mu ((e\kappa + g_V)\gamma_\nu + g_A \gamma_\nu \gamma_5)\psi_\mu + ...\right],\end{aligned}$$

Can one find $g_V$ and $g_A$ that will satisfy all constraints?

(and forget for now about embedding it into SM)

# Summary of constraints on $g_V$, $g_A$

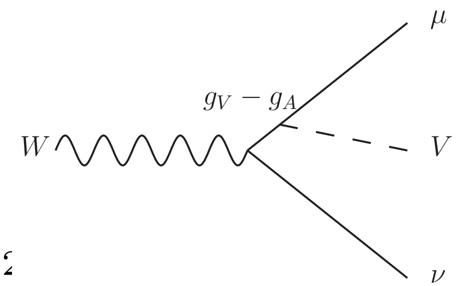



Notice that small $g_A$ is required to tune away g-2 of the muon. (Axial vector contribution to g-2 is enhanced by $(m_\mu/m_V)^2$. ) Values of coupling $\kappa$ chosen at the border-line of g-2 of electron constraint.

# Most uncomfortable constraint of all !! W decay

- We insisted on no couplings of V to neutrinos and $g_V >> g_A$. This is equivalent to charge non-conservation in processes with production of $\mu\nu_\mu$ pairs via weak processes.

- One should expect $(E/m_V)^2$ enhancement for generic values of $g_{V,A}$ and $(m_\mu/m_V)^2$ enhancement for $g_V = g_A$.




$$\Gamma\left(W \to \mu\nu V\right) = \frac{g_V^2}{512\sqrt{2}\pi^3}\frac{G_F m_W^5}{m_V^2}$$
$$= 1.74\ \mathrm{GeV}\left(\frac{g_V}{10^{-2}}\right)^2\left(\frac{10\ \mathrm{MeV}}{m_V}\right)^2$$

- It is a *huge effect*, underscoring the necessity to deal with embedding of a new force within SM. Model with pure RH current escapes this most uncomfortable constraint. *One needs a proper embedding into SM representations – otherwise nonsense at high energy.*

# Other possibilities??

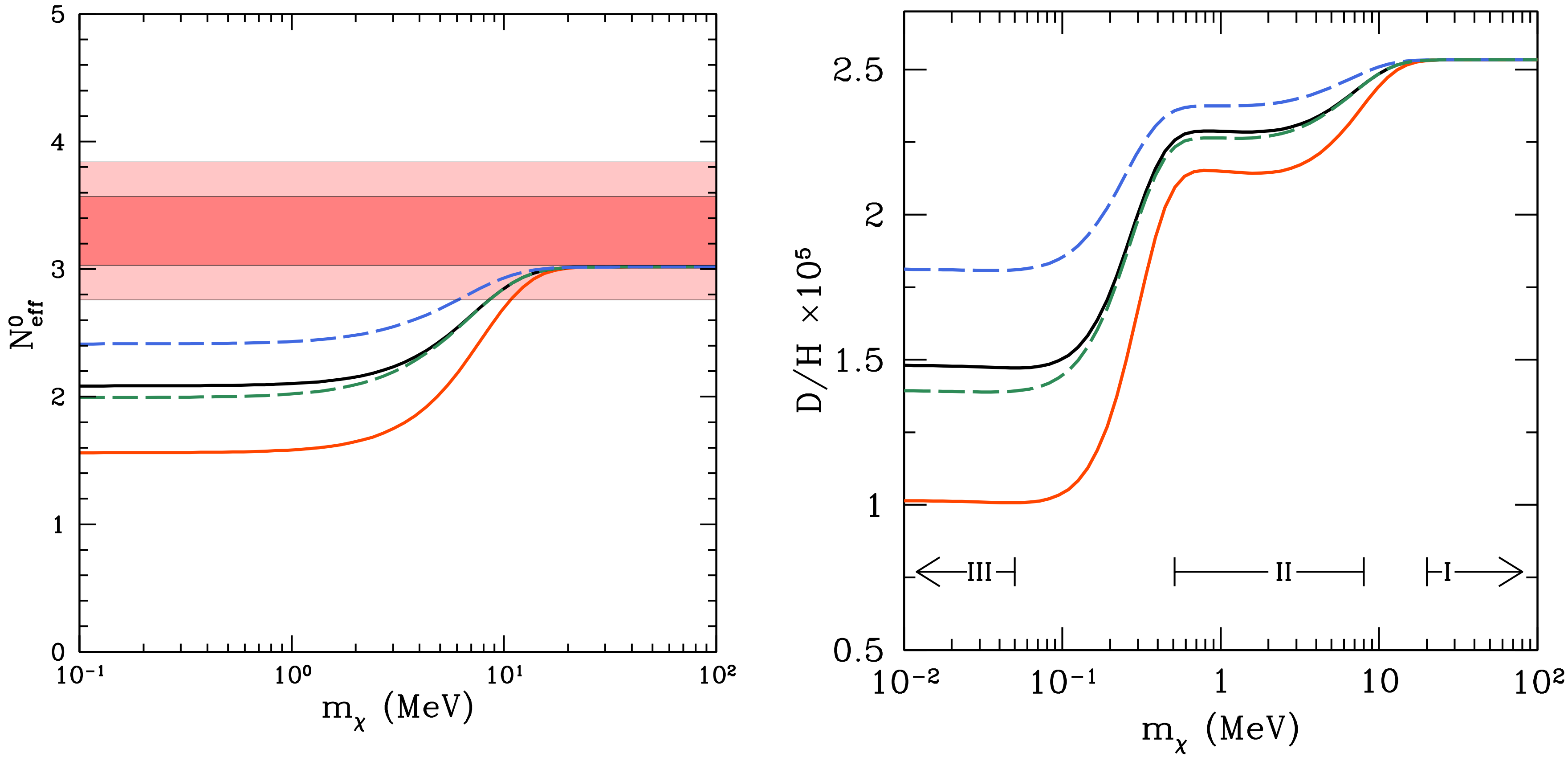
Project with Eder Izaguirre and Gordan Krnjaic,
to appear next month

- *How about the scalar force* – call it $\phi$ – that provides e-p repulsion and fixes $r_p$ discrepancies at least between normal H and $\mu$H?
- Couplings will be very small, and the mass will be small, O(200 keV), $y_e y_p / e^2 \sim -10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of constraints
- Our proposal: use small *underground accelerators* coupled with large scale detectors such as *Borexino, Super-K* etc… Up to ~ 20 MeV kinematic reach is available due to nuclear binding.
- Use of nuclear reactions and scintillator or water Cerenkov detectors provide direct sensitivity to the product $y_e y_p$

# O(0.5 MeV) scalars with O($10^{-4}$) couplings – an unexpected blind spot

1. No tree level FCNC, and too weakly coupled to be killed by loop effects in flavor. Too weakly coupled to be excluded by e.g. LSND
2. Too heavy to be produced in regular stars thermally – no strong energy loss constraints.
3. Too strongly coupled to matter and *not* coupled to neutrinos – thermalized during the SN explosions. No energy loss, no effect on neutrino spectra.
4. Being produced inside the Sun in the pp chain, particles can get absorbed/decay before exiting the Sun.
5. In cosmology, such particles give *negative* shift to $N_{eff}$ , and are "gone" before the main sequence of BBN reactions begins.

# Cosmological "effective" $N_{eff}$




From Nollett, Steigman 2013; scalar - blue curve. $N_{\rm eff}$ of 2.5 is probably still OK, and if not it is easy to arrange a positive contribution to $N_{\rm eff}$ (e.g. new neutrinos.)

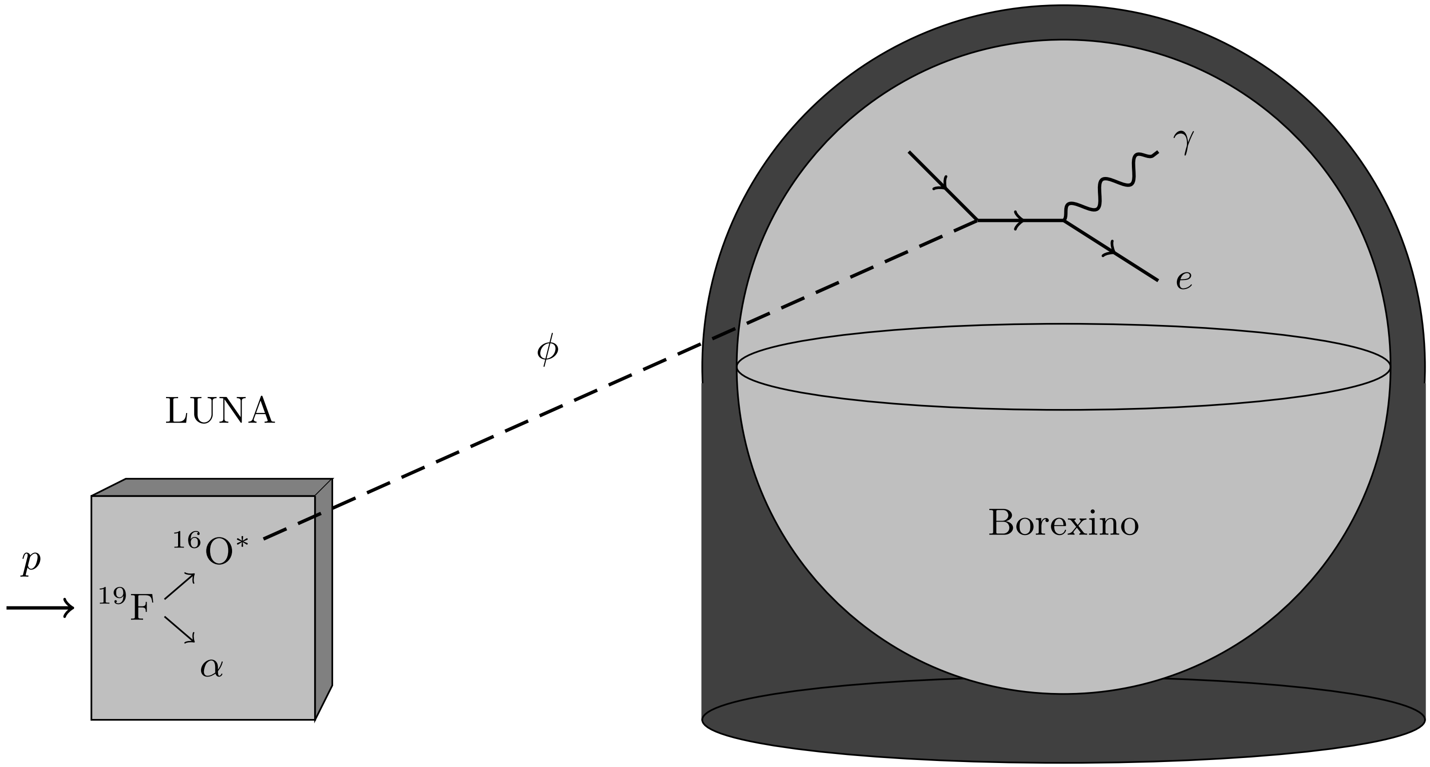
# What are underground accelerators ???

- Built for the needs of measuring rare reactions in nuclear physics. Relatively cheap. Example: LUNA at LNGS.
- Using proton of $^{3}He$ on targets with energy < 0.5 MeV, and in the future up to 3 MeV.
- Located in the cleanest possible environments.
- Other projects in the works (DIANA) at Sanford Lab.

Future Luna MV

Luna 400 keV

# Main idea schematically




*Potential problem*: nuclear reactions can liberate some neutrons (e.g. via $^{19}$F $+\alpha \rightarrow$ $^{22}$Na +n), and there are stringent requirements on not increasing *n* background at the location of DM experiments.

# Production stage; candidate reactions

- $T + p \rightarrow {}^{4}\mathrm{He} + \gamma$ ;

Up to 20 MeV mass can be explored, production x-section: ~10$\mu$bn.

- ${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$ $\quad$ (${}^{7}\mathrm{Li} + p \rightarrow {}^{8}\mathrm{Be} + \gamma$; ${}^{11}\mathrm{B} + p \rightarrow {}^{12}\mathrm{C} + \gamma$…)

Very similar; was studied by LUNA before.

- Photon-less reactions leading to excited nuclear states. Whenever you can emit gamma, you can emit scalar particle.

${}^{6}\mathrm{Li} + {}^{3}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{p}$

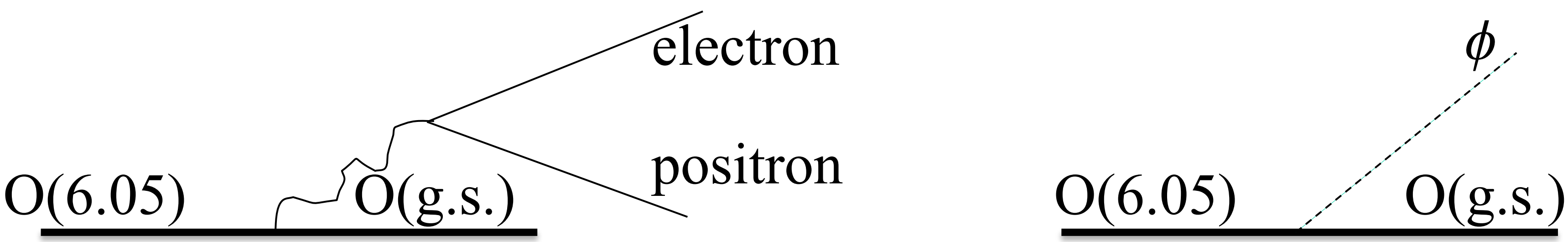
${}^{19}\mathrm{F} + p \rightarrow {}^{16}\mathrm{O}^{*} + {}^{4}\mathrm{He}$, …

- Reaction cross sections in 10's of milli-barn.

# $^{19}F + p \rightarrow {}^{16}O^* + {}^{4}He$ is the best candidate!

- $^{19}F + p \rightarrow {}^{16}O + {}^{4}He$ populates the first excited 6.05 MeV state of oxygen. Cross sections are in ~ 20 mbn range [i.e. *not small*].
- Normal decay of O(6.05 MeV) is due to $0^+ \rightarrow 0^+$ transition with the emission of electron-positron pair. Very suppressed.
- *The enhancement of the branching is*

$$Br[O(6.05) \rightarrow O(g.s.) + \phi] = 3600 * (y_p{}^2/e^2)$$




6.05 MeV is in the "cleanest" region of Borexino – no $^{208}Tl$ background.

# Calculation of the production rate

- At E ~ MeV, nuclear reactions are improbable as Coulomb stopping is more efficient. Probability is given by

$$P(E_0) = \int_0^{E_0} dE \, \frac{\sigma_{\mathrm{nucl}}(E) n_{\mathrm{target}}}{|dE/dx|}$$

- For *p* on $^{19}$F reaction, we calculate the probability of exciting 6.05 MeV oxygen state as P(3 MeV) = 6 × $10^{-6}$.

- With achievable currents on the order of ~ 10 mAmp,

the Production Rate = $(y_p/e)^2 \times 10^{15}$ Hz.

# Advantage of being clean…

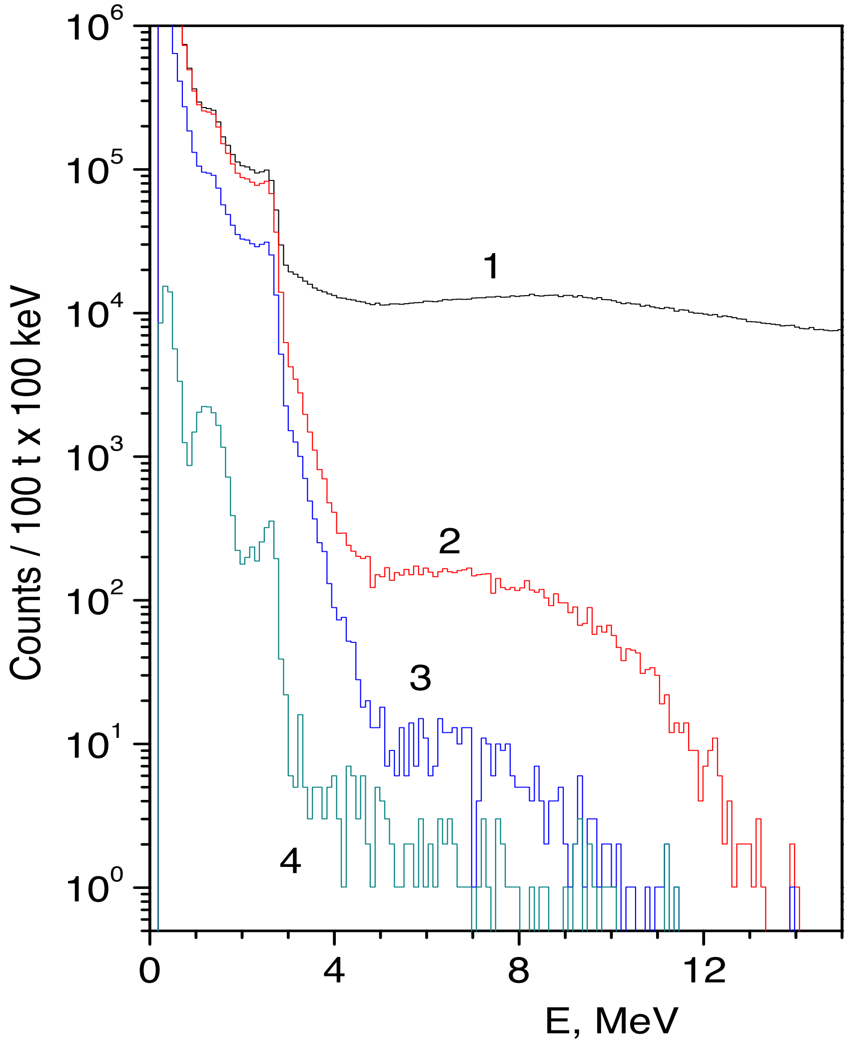
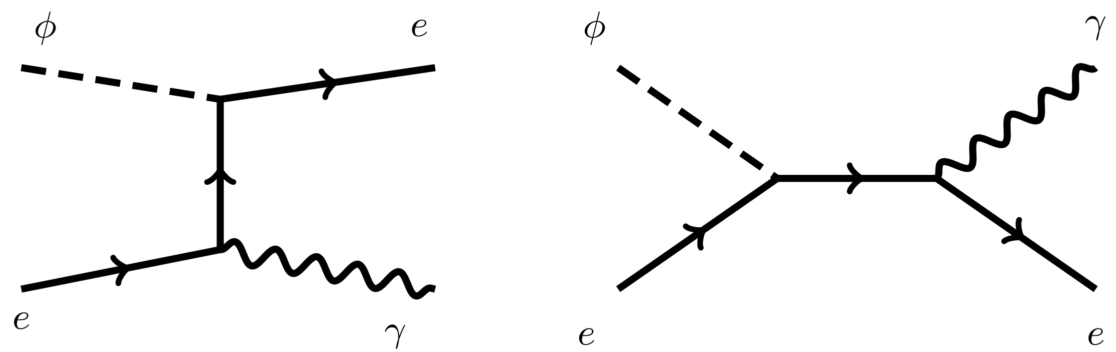



FIG. 2. Energy spectra of the events surviving incremental selection cuts. From top to bottom: (1) raw spectrum; (2) 2 ms post-muon veto cut; (3) 20 s after muons crossing the SSS cut; (4) FV cut. See text for details.

- If new particle is stable on the scale of underground Lab, it will fly into e.g. Borexino etc causing $e + \phi \rightarrow e + \gamma$, and releasing O (6-20) MeV energy depending on the reaction.
- In the cleanest experiments, e.g. Borexino, above 5 MeV there is no $^{208}$Tl events, and the background for this search are only $^{8}$B neutrinos.

# Scattering rate



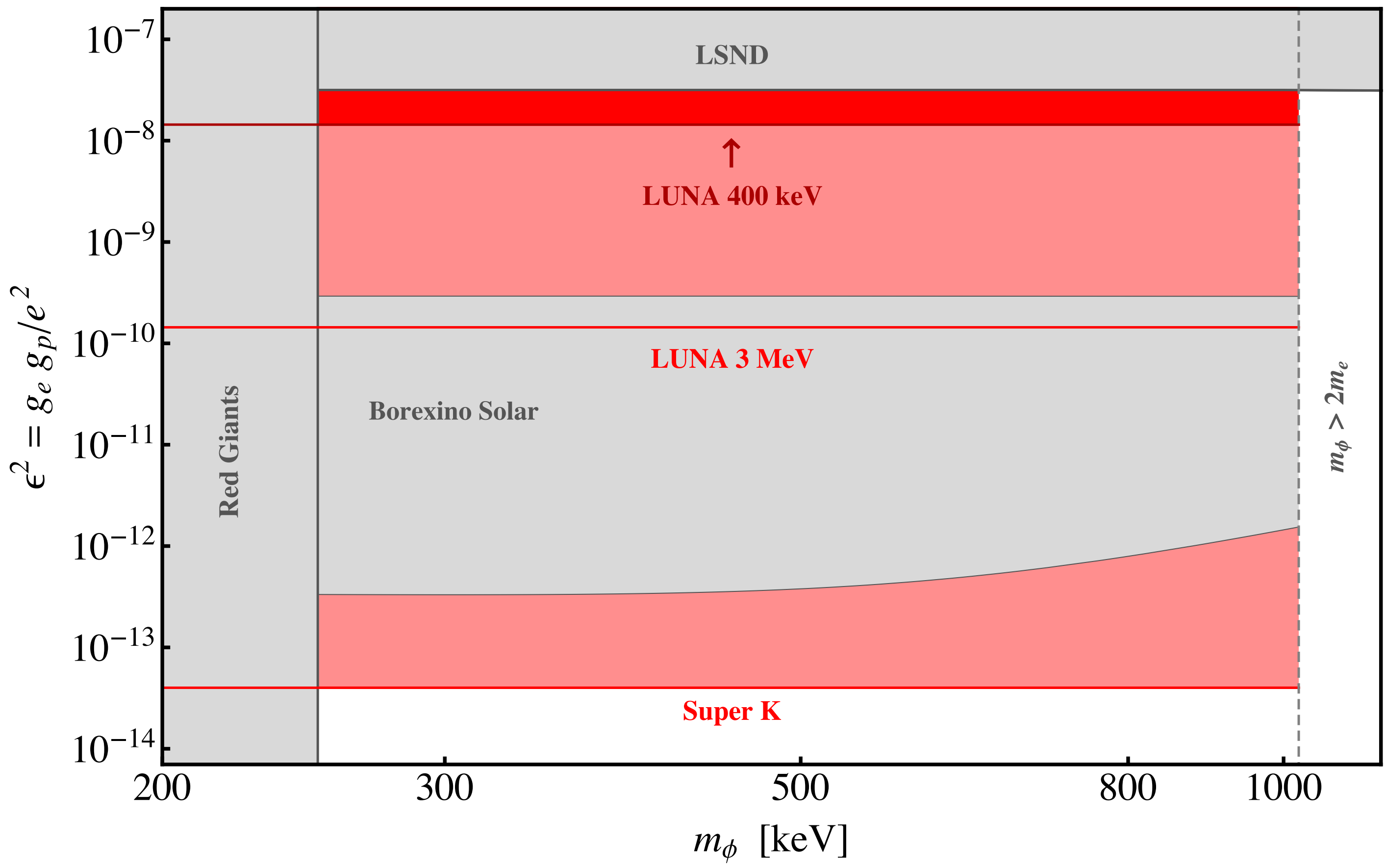

- Scattering rate is readily computable, with cross sections

$$\sigma(e+\phi \rightarrow e+\gamma) \sim (y_e/e)^2 \times \sigma_{\text{Compton}}$$

In Borexino [that has good energy resolution] all events are recorded and will appear at 6 MeV. In Super-K, only the most energetic electrons > 4-5 MeV can be detected.

# Sensitivity plot

- 6.05 MeV is in the "cleanest" region of Borexino – no $^{208}$Tl background. $r_p$ *relevant region* (*at the boundary of g-2*) *can be fully covered.*



# Conclusions

- Measurement of Lamb shift in $\mu$H is very precise & discrepant by $7\sigma$ with expectations from $r_p$ measured in scattering and hydrogen spectroscopy → *think about g-2, do not ignore this problem.*
- New physics "explanations" are problematic because of $\sim 10^4 G_F$ size of the effect – difficult to embed in the SM. Have to tune many observables (g-2 of the muon, possibly neutron scattering)…
- Very light scalar particle (~ 0.2-0.5 MeV), providing additional repulsion between protons and electrons is one of the logical possibilities that could help reconciling $e$H and $\mu$H results.
- Can be very efficiently searched for in underground accelerators as source of exotic particles and large clean detectors (Borexion, Super-K, …).
- Many orders of magnitude in small coupling constants

  can be covered….
- It looks as reasonably cost-effective search.